Machine Vision for Rapid Geometric Modeling

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Abstract

A method is presented for constructing geometric design data from noisy 3-D sensor measurements of physical parts. A complete 3-D data set have to be produced from several partial data sets. Model building tools for free form surfaces as well as irregular and standard geometric shapes are presented. In particular, NURBS, superellipsoids and Delaunay triangulations are employed. The data interpretation should be able to map the recovered shape of the part to appropriate design primitives. The resulting model description is a procedural CAD model which can represent the structural properties of a part in addition to low level geometric primitives. Finally, the model is translated to standard product data exchange format to enable data sharing.

1 Introduction

Sculptured surfaces are widely used, for example, in designing car and ship parts. The design of free form shapes, however, is relatively time consuming and requires typically extensive knowledge about the modeling primitives, such as splines. The task could be made easier by constructing a model automatically using sensory measurements, for example, from a clay model of a part. We propose here an approach for integrating an intelligent sensory system into a CAD system in order to produce an initial geometric model rapidly. The designer should be able modify the obtained model which is often necessary because the design changes during the development process.

We are employing non-contact optical sensors for data acquisition to be able to acquire dense data set fast. Dense data are required for modeling sculptured surfaces accurately. In order to model solid objects we have to obtain a complete 3-D data set. Laser range finders, however, produce only partial data from a single viewpoint at the time and the complete data have to be combined from partial data sets acquired from different viewpoints. The problem requires estimation of relative translation and rotation parameters between partial data sets obtained from different vantage points as well as combination of data into a common coordinate frame. The data interpretation part constructs a geometric model from the data by fitting models. The obtained representation of the data is compatible with the representations employed in modeling systems and product data exchange formats.

Our approach constructs *procedural CAD models* in order to represent low level geometry of the part as well as convey its overall structure. Structural information is vital for analysis, simulation and process planning purposes. Procedural models are also relatively easy to modify. They are also convenient in representing intersections of parametric surfaces. The intersection is described in the procedure and it can be approximated in the level of required accuracy when it is actually needed. The constructed model should employ the model primitives used in CAD systems. It must be translated into standard product data exchange format to enable data sharing, and consequently, concurrent engineering [5]. The proposed system is depicted as a part of concurrent engineering environment in Figure 1.

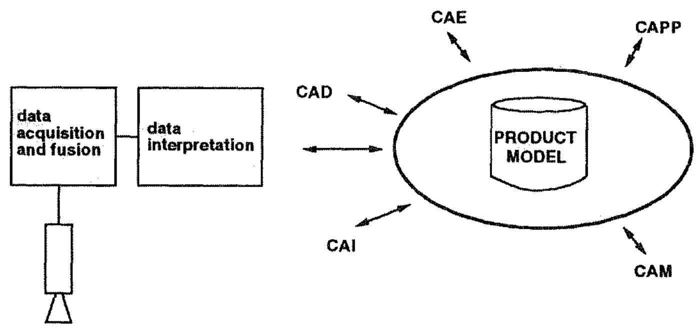

Figure 1: The proposed system as a part of a concurrent engineering environment. The CAX processes are Design, Engineering, Process Planning, Manufacturing and Inspection.

The organization of this paper is as follows. In section 2 we address shape representation issues in machine vision and CAGD. Section 3 outlines the proposed approach and describes briefly some methods used in model construction. In section 4 we show some examples of data interpretation using real and simulated range data. Finally, in section 5 we conclude and discuss some areas requiring future research.

2 Representation of shape

Constructive Solid Geometry (CSG) and Boundary Representation (B-rep) are widely used in solid modeling systems [13]. Several CAD-systems are hybrid systems that employ multiple representations in order to provide efficient tools for different design tasks and to overcome the shortcomings of each single representation. For instance, Alpha_1 [1] uses NURBS for designing free form shapes and allows CSG type Boolean operations on solids as well as design by manufacturing features.

It seems, analogous to the design, that there is no single representation in Computer Vision that could be used for recovering an appropriate shape description from sensor data in all situations. In general, the representations can be classified into surface, volumetric and sweep representations [3]. In order to facilitate modeling of different shapes from sensor data we are employing multiple representations. An optimal triangulation is generated for modeling polygonal and complicated irregular shapes which may have arbitrary topology. It can also serve as a worst case representation, if no other method is appropriate. NURBS are used for modeling free form surfaces because of their continuity and local control properties. In addition, trimmed surfaces are used when rectangular arrangement of tensor product surfaces is not suitable. Furthermore, they are included in IGES product data exchange standard which facilitates data sharing and concurrent engineering. Superellipsoid models are used to detect overall part structure which allows us to use more efficient model primitives that are helpful in part analysis and process planning.

3 An overview of the proposed system

The data acquisition is performed by a laser range finder. The accuracy of such sensory system is suitable for measuring artifacts of large scale. Optical non-contact sensors measure only from bounding surfaces of an object, hence the interior of solids are not modeled. A multipart artifact must be disassembled if one wants to produce a description of the joints as well. Otherwise, data have to be segmented into meaningful parts. Physical measurements are subject to various noise effects. In the case of laser range finders, the noise process deviates from Gaussian and the may occur outliers. We apply nonlinear RLTS filters [8] based on robust estimation theory for separating the desired part in degraded data from the undesired part while preserving the structure of the signal.

In order to produce a complete 3-D data set, the transformation between partial data sets have to be estimated and the data combined into common coordinate frame. This is done by combining the data sets from each viewpoint incrementally. A method based on iterative closest point procedure [4] is used for solving the rotation and transformation which minimizes the distances of points from the surfaces in the model constructed so far. A more thorough description of the view registration and preliminary experimental results are given in [16, 10].

The 3-D data set is represented as a collection of triangles. In particular, a 2/3 Delaunay triangulation is generated. The triangulation process is based on the algorithm given in [7]. It is refined so that the accuracy meets a user defined tolerance value [10]. Triangulations convey very little structural information but can be used as a worst case representation if no other method is appropriate, e.g., in the case of natural objects that do not consist of smooth surfaces. Moreover, the resulting triangulation can be used as an input to more advanced surface approximation procedures as well as an initial mesh for analysis and simulation processes.

The CAD model building strategy is chosen based on the obtained volumetric and surface data descriptions and their quality. The basic idea is to find out if the part is approximately a standard primitive solid or has structure such as symmetry. A superellipsoid model [2, 15] is recovered for each part to capture both overall structure and global deformations. An implicit equation for superellipsoid surface is defined as follows:

$$f(x,y,z) = \left(\left(\frac{x}{a_1}\right)^{\frac{2}{\varepsilon_2}} + \left(\frac{y}{a_2}\right)^{\frac{2}{\varepsilon_2}} \right)^{\frac{\varepsilon_2}{\varepsilon_1}} + \left(\frac{z}{a_3}\right)^{\frac{2}{\varepsilon_1}} = 1, \qquad (1)$$

where a_1, a_2, and a_3 define the size in x-, y- and z-axis direction. ε_1 and ε_2 are the shape (squareness) parameters in the latitude and in the longitude plane, respectively. The obtained shapes are classified into categories so that an appropriate CAD modeling primitive can be selected [9]. The superellipsoid method does not give the part dimensions very accurately. In the case of rotationally symmetric objects, for instance, the accurate dimensions are obtained by fitting conic sections [12].

The surfaces are approximated using NURBS surfaces because of their good continuity and local control properties. NURBS is defined as a bivariate polynomial function of parameters u and v as follows:

$$S(u,v) = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} h_{i,j} B_{i,j} N_{i,k}(u) M_{j,l}(v)}{\sum_{i=1}^{n}\sum_{j=1}^{m} h_{i,j} N_{i,k}(u) M_{j,l}(v)}, \tag{2}$$

where $N_{i,k}$ and $M_{j,l}$ are the basis functions, $h_{i,j}$ are the weights, and the $B_{i,j}$'s are the control points. n and m identify the number of control point vertices in each direction. The complexity of the underlying surface is determined by a local surface characterization process. An appropriate size for control point mesh is estimated based on the number of geometrically homogeneous surface patches detected in the characterization process [9]. The locations of the control points $B_{i,j}$ are estimated by minimizing error in least squares sense. The approximation is refined to meet a user given tolerance value by knot insertion [11]. Surface discontinuities are detected where rapid changes in surface normal occur. B-splines are subdivided where discontinuities take place [6].

The obtained model data is represented both in procedural modeling language and in standard product data exchange format (IGES) to be able to share the model with other subsystems. Some of the obtained model primitives can be directly mapped to primitive manufacturing operations in computer aided process planning (CAPP). Rotationally symmetric parts can be mapped to a manufacturing stage performed on a CNC lathe, for example. Novel manufacturing processes, such as MD* [17], can fabricate very complicated shapes easily with less structural information. The process planning is basically independent from part complexity because 3-D shapes are build incrementally from cross-sectional layers. Each layer is then sprayed using a disposable mask which has a shape of cross-section.

4 Examples

In this section we show some examples of building CAD models from simulated and real range data. Constructed models of standard geometric and free-form shapes as well as surfaces of arbitrary topology are shown. The test pieces are illustrated in Figure 2 where the Cylindrical Pin is simulated data and the Face Mask image and the Hand image are from NRCC [14] range image library.

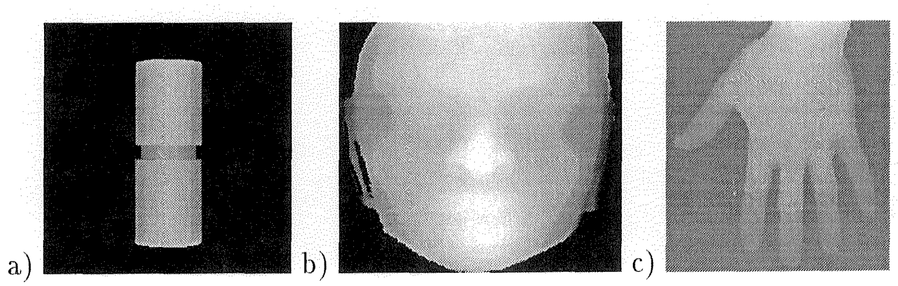

Figure 2: Example test data: a) The Cylindrical Pin is rotationally symmetric shape, b) the Face Mask is a free form shape and c) the Hand is a free-form shape with several branches.

Noise attenuation and especially outlier rejection are important to be able to obtain reliable results from least squares fitting procedures. Robust RLTS filtering is performed to recover the signal structure from noisy observations. Filtering examples are given in [8, 9].

2/3 Delaunay triangulation is performed on test data. Triangulations are employed in modeling polygonal objects and irregular shapes where the surfaces may not be smooth. Example triangulations of the Face Mask and Hand data are shown in Figure 3.

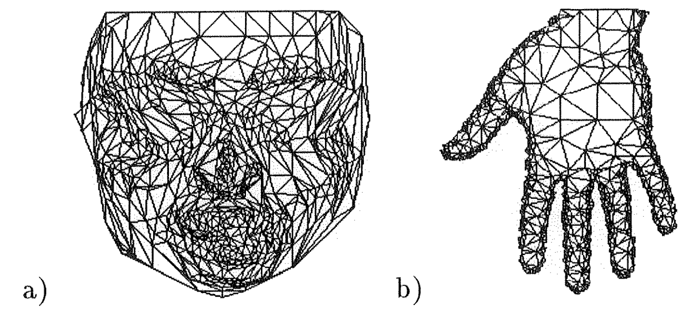

Figure 3: Delaunay triangulations of a) the Face Mask and b) the Hand data using tolerance value 0.4 mm.

The superellipsoid model recovery is used to reveal global shape properties. The obtained shape parameters are used as a hypothesis to invoke the appropriate model building procedure. The superellipsoids for test pieces are depicted in Figure 4. The shape parameters reveal the rotational symmetry of the Cylindrical Pin. The quality of the fit is also high, hence surface of revolution modeling primitive is selected. The quality of the fit is low for the Face Mask and the Hand data and they are modeled as a collection of bounding surfaces.

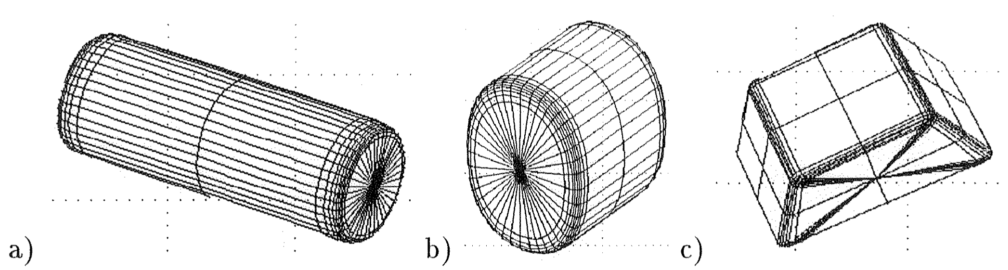

Figure 4: The obtained superellipsoid models of the test pieces: a) the Cylindrical Pin, b) the Face mask, and c) the Hand

The free-form surfaces are approximated by NURBS. The locus of the control points is solved minimizing least squares error norm. Rectangular arrangement of tensor product surfaces is not appropriate in all situations. Trimmed surfaces provide a convenient engineering tool for modeling surfaces of arbitrary topology. Boundaries of the surface are used to compute trimming curves which divide the surface into valid and invalid parts. Approximating NURBS surfaces for test pieces are depicted in Figure 5. The surface description is refined to meet user defined tolerance value by inserting knots and, as a consequence, more control points. An example of the refinement by knot insertion for a profile from the Face Mask is depicted in Figure 6.

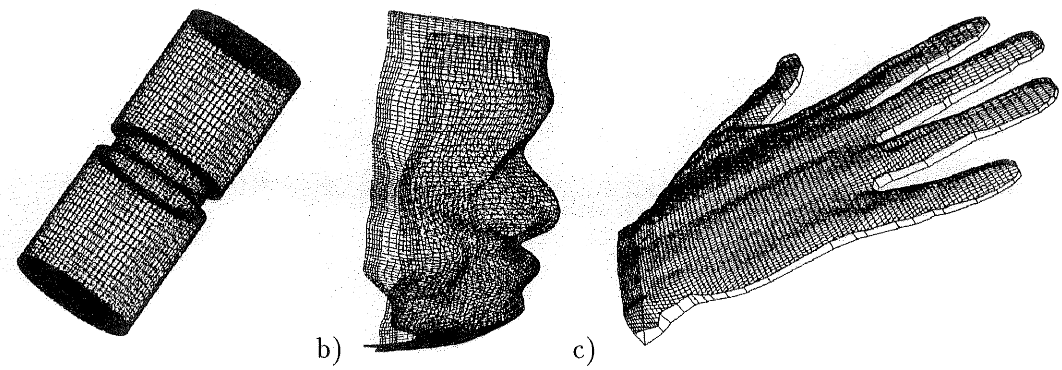
a) b) c)

Figure 5: Approximating NURBS surfaces for the test pieces: a) The Cylindrical Pin is modeled as a surface of revolution, b) the Face Mask is a tensor product surface and, c) the Hand is a trimmed surface.

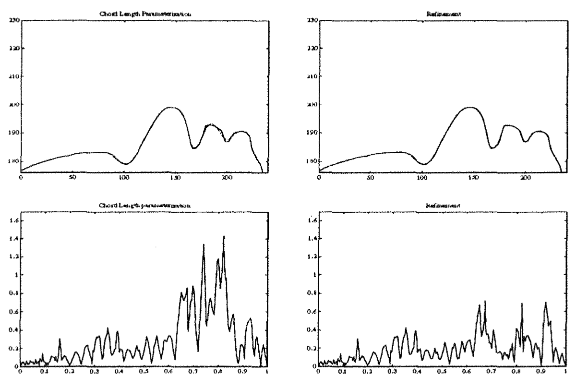

Figure 6: A profile from the Face Mask data and its B-spline approximation (dotted line) before (left) and after (right) the refinement by knot insertion. A tolerance value of 1 mm is used. The corresponding error distances are depicted below.

The obtained model procedure which generates the part geometry is imported into Alpha_1 [1] solid modeling system. Procedural models are able to convey information about the part structure, for example, the rotational symmetry of the cylindrical pin. Moreover, the surface intersection in the trimming operation for the Hand data is described in the procedure and the intersection can be approximated only when needed: less accurately for display purposes and very accurately for toolpath generation. A part of a model procedure generating a solid of revolution and a part of the corresponding IGES file are illustrated in Figure 7.

5 Conclusion

We presented a computer-aided engineering tool where an intelligent sensory system is integrated into a design automation environment. The task at hand is to build an initial geometric model of a part using 3-D sensor data. In particular, modeling of sculptured shapes could benefit from rapidly produced geometric models. It is important that the initial model can be modified because the design typically evolves.

```
...
p12 := projPt(0.000000,80.61196,27.174069,1.0);
p13 := projPt(0.000000,100.26872,27.123658,1.0);
p14 := projPt(0.000000,120.01186,27.189411,1.0);
p15_1 := projPt(0.000000,129.88000,27.140000,1.0);
p15_2 := projPt(0.000000,129.88000,27.140000,1.0);
p15_3 := projPt(0.000000,129.88000,27.140000,1.0);
p15_4 := projPt(0.000000,129.88000,27.140000,1.0);
p16 := projPt(0.000000,129.88000,0.00000,1.0);
);

(
Revcurv := curve(parminfo(cubic,ec_open,MyKnotlist),
list( p0, p1_1, p1_2, p1_3, p1_4, p2, p3, p4, p5_1, p5_2,
p5_3, p5_4, p6_1, p6_2, p6_3, p6_4, p7, p8, p9, p10_1,
p10_2, p10_3, p10_4, p11_1, p11_2, p11_3, p11_4, p12, p13, p14,
p15_1,p15_2,p15_3,p15_4, p16));
RevSurf := srfOfRevolution(Yaxis,Revcurv,nil,nil);
Modsolid := shell(RevSurf);
);
```

```
IGES OUTPUT FROM Rapid Prototyping System                              S0000001
1H,,1H;,,12H symnavy.igs,20HRapid Prototyping   ,5H1.0.0,32,38,6,38,15,,G      1
1.,2,2HMM,32,5.,13H920821.120414,0.00001,1000.0000,2HVK,,9,0;          G      2
     162       1       0       1               0       0       00000001D0000001
     162       0       0       1       0                              1D0000002
     126       2       0       1       0       0       0              1D0000003
     126       0       0      32       0                              1D0000004
162,3,1.0,0.0,0.0,0.0,0.0,1.0,0.0,                                    1P0000001
126,34,3,0,0,0,0,                                                     3P0000002
000.00000,000.00000,000.00000,000.00000,000.03125,000.06250,          3P0000003
000.09375,000.12500,000.15625,000.18750,000.21875,000.25000,          3P0000004
```

Figure 7: Model data for the Cylindrical Pin: a part of the Alpha_1 model (left), and a part of the IGES description (right).

Physical measurements are subject to noise which must be attenuated without distorting the underlying signal in order to make accurate model construction possible. Data have to be acquired from several viewpoints and fused into a complete 3-D data set in a common coordinate frame. The data interpretation is produced by fitting models. Multiple representations are employed in order to model different shapes efficiently. The aim is to obtain a representation of the part geometry using CAD modeling primitives. The result is a procedural CAD model which is able to convey structural information about the part in addition to low level geometric data. Furthermore, the designer can modify the procedure and refine the model as the design evolves. The model is translated to standard product data exchange format to facilitate concurrent engineering.

The ongoing and future research is directed toward refining and extending the data acquisition process in order to register free form shapes accurately. Furthermore, the integration of engineering analysis tools into the system is under development.

Acknowledgements

We want to thank Dr. Beth Cobb and Prof. Rich Riesenfeld for providing us Alpha_1 system, and for their help and hospitality while studying it. The Academy of Finland, The Foundation Suomen Kulttuurirahasto, and the University of Oulu, Finland are gratefully acknowledged for financial support. The facilities were partly provided by Navy Grant N00014-92-J-1647, AFOSR Grant 88-0296; Army/DAAL 03-89-C-0031PRI; NSF Grants CISE/CDA 88-22719, IRI 89-06770, and ASC 91 0813; and Du Pont Corporation

6 REFERENCES

[1] Alpha_1 User's Manual (1992) University of Utah. USA.

[2] Barr, A., "Superquadrics and Angle Preserving Transformations", IEEE Computer Graphics and Applications, Vol. 1, pp. 11-23, 1981.

[3] Bhanu, B., Ho, C., "CAD-Based 3-D Object Representation for Robot Vision", IEEE Computer, August, pp. 19-35, 1987.

[4] Besl, P., McKay, N., "A Method for Registration of 3-D Shapes", IEEE Transaction on Pattern Analysis and Machine Intelligence, Vol. 14, No. 2, pp. 239-256, 1992.

[5] Carver, G., Bloom, H., "Concurrent Engineering through Product Data Standards", In: Control and Dynamic Systems, Vol. 45: Manufacturing and Automation Systems: Techniques and Technologies, Academic Press, pp. 31-109, 1992.

[6] Cohen, E., Lyche, T., Riesenfeld, R., "Discrete B-Splines and Subdivision Techniques in Computer Aided Geometric Design and Computer Graphics", Computer Graphics And Image Processing, 14, pp. 87-111, 1980.

[7] Field, D., "A Generic Delaunay Triangulation Algorithm for Finite Element Meshes", Adv. Eng. Software, 1991, Vol. 13, No. 5/6 combined, pp. 263-272, 1991.

[8] Koivunen, V. "Robust Approach to Filtering of Scalar and Vector Valued Signals", IEEE Workshop on Image and Multidimensional Signal Processing, Cannes, France, 1993.

[9] Koivunen, V., Bajcsy, R., "Geometric Methods for Building CAD Models from Range Data", In: Geometric Methods in Computer Vision II, SPIE Vol. 2031, San Diego, 1993.

[10] Koivunen, V., Vezien J-M., Bajcsy, R., "Multiple Representation Approach to Geometric Model Construction from Range Data", Technical Report MS-CIS-93-66, University of Pennsylvania, 1993.

[11] Piegl, L., "Modifying the shape of rational B-splines. Part 2: Surfaces", Computer Aided Design, Vol. 21, No. 9, pp. 538-546, 1989.

[12] Pratt, V., " Direct Least-Squares Fitting of Algebraic Surfaces" Computer Graphics 21, No. 4, pp. 145-152, 1987.

[13] Requicha, A., Voelcker, H., "Solid Modeling: A Historical Summary and Contemporary Assessment", IEEE Computer Graphics and Applications, Vol. 2, No. 2, pp. 9-24, 1982.

[14] Rioux, M., Cornoyer, L. "The NRCC Three Dimensional Image Data Files". CNRC 29077, National Research Council of Canada, 1988.

[15] Solina, F., Bajcsy, R., "Recovery of Parametric Models from Range Images: The case of Superquadrics with Global Deformations", IEEE Transactions on Pattern Analysis and Machine Intelligence, PAMI-12, No. 2, pp. 131-147, 1990.

[16] Vezien J-M, "Data Acquisition and Registration of Range Images for Reverse Engineering Applications", Technical Report, University of Pennsylvania, Department of Computer Science, July, 1993.

[17] Weiss, L., Prinz, F. & Siewiork, D., "A Framework for Thermal Spray Shape Deposition: The MD* System", Solid Freeform Fabrication Symposium, Austin, Texas, USA, 1991.